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Simulation and analysis of PV module performance by innovative sorting methods

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Abstract

Sorting of solar cells is a vital step to achieve the predetermined power out of the photovoltaic module, nevertheless there is a lack of detailed investigations of all relevant parameters defining the global module efficiency. Sorting methods tend to rely on simple electrical parameters such as P_{MAX}, I_{MPP}, and I_{SC}. However, it is crucial to take into consideration that the performance of individual cells will be changed after the encapsulation. Therefore, in this study potential changes in operating parameters such as J_{SC} and R_{ser} are integrated in the sorting step. It is a fact that at low light intensities the impact of R_{shunt} on module performance is more critical compared to standard test conditions (STC) where the actual measurements are carried out. In addition, the optical parameters of cells are subject to change after the encapsulation. That is why, inclusion of optical parameters such as reflectance into the sorting step is analysed. In this study, innovative sorting methods with the inclusion of R_{shunt} and reflectance were introduced. The results show that, at low light intensities conventional sorting approach can be extended with a combination of R_{shunt} and other electrical parameters to achieve higher module efficiencies up to 0.1 % absolute. In addition, adding optical reflectance into the sorting parameters set current mismatches in modules can be minimized.

Keywords: cell sorting; module simulation; low-light behavior

1. Introduction

For production of optimized modules sorting of solar cells into different classes by predefined criteria is indispensable. However, only a limited number of studies have been conducted on the analysis of

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sorting methods. In this study we simulate and analyze new cell sorting approaches. In the first part we concentrate on the importance of considering the changes in cell characteristics due to encapsulation for more accurate evaluation of the sorting methods used. In the second part we investigate the potential of adding new parameters such as weighted reflection and R_{shunt} into the sorting step thereby giving a special weight to low-light behavior.

2. Structure of simulations

In this study, data for the module simulations were obtained from the dark and illuminated *I-V* measurements (1000 W/m^2 and 500 W/m^2) of identically processed 5" multicrystalline silicon solar cells fabricated from the same batch. After the measurements the *I-V* curves were fitted to the conventional double diode model (DDM). Dark *I-V* measurements allow an accurate determination of R_{shunt}. In addition, fitting the data from half sun measurements validated the linear behavior between irradiance and photo current J_{ph}. This relationship is also further applied to lower irradiance values. To minimize fitting errors a constraint was set so that I_{MPP}, V_{OC}, V_{MPP} and I_{SC} values obtained from the fits and measurements had to lie within an error range of ±0.3 % abs. Cells used in this study have an average efficiency of 15.6 % with the best and worse cells having 16.42 % and 14.96 %, respectively. Standard deviation is 0.35 % abs.

For the module simulations an extended DDM was used. To build the electrical model for the module, DDM for the cells must be extended. The main advantage of the used model is that the DDM parameters (J_{ph}, J_{o1}, J_{o2}, R_{ser} and R_{shunt}) of each cell in the module are unique and hence the differences between the cells are distinguished at highest extent, which is crucial to analyze effects of different sorting approaches and mismatches. The interconnect ribbon between adjacent cells is modeled with an extra resistance in series with R_{ser}, which is the dominant factor for power loss in modules. In addition, encapsulation effects on I_{SC} and hence J_{ph} are considered as well, which are neglected in commercial sorting mechanisms.

In industry it is a common practice to sort out cells with shunts. The elimination of cells with shunts is directly coupled with a small R_{shunt}. To define the lowest acceptable value of R_{shunt} in the simulations with 60 cells DDM parameters except R_{shunt} were chosen to be identical for each cell and R_{shunt} was increased gradually in successive simulation steps. As R_{shunt} reaches a certain level its effects on power output can be neglected. However, values less than 1000 Ωcm^2 deteriorate the power output significantly. Hence, cells not fulfilling this criterion were sorted out. This is in accordance with previous studies [1].

3. Simulation results

3.1. Simulation of changes in module performance due to encapsulation

Photovoltaic module simulation methods by a simple serial connection of individual cells excluding encapsulation effects on the DDM parameters remain incomplete. Depending on the matching of refractive indices of the antireflection coating and glass/EVA stack, I_{SC} of the module can be larger or smaller than of the cell [2]. In the first part of this study, to illustrate these effects, modules consisting of 60 in series connected cells were simulated at STC. J_{ph} of each cell in the module was varied between 97 % and 103 % of the original value to account for the above mentioned change. Additional series resistance for each cell due to interconnect strings was varied between 0 Ωcm^2 and 2 Ωcm^2. Results of these simulations are depicted in Fig. 1.

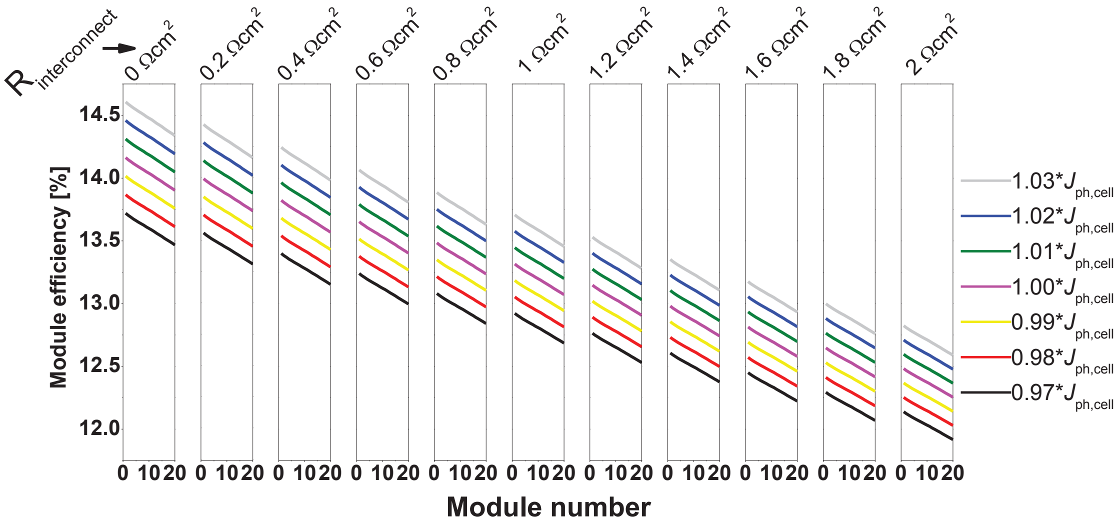

Fig. 1. Simulated module efficiencies after the cells are sorted in descending order by cell efficiency taking changes in J_{ph} due to encapsulation and interconnection resistances into consideration

For the module simulations characterization data of 79 cells were used. In this simulation scenario, the cells were sorted in descending order according to their efficiencies. The first simulated module (denoted as module number 1 on the x-axis) consists of the cells 1-60. Since the cells were sorted in descending order this first module has the highest average efficiency of the cells. Subsequently, module number 2 consists of the cells 2-61 and module number 20 corresponds to the cells 20-79. With this method a controlled drop in module efficiency (ηmod) with increasing module number was achieved. To demonstrate the influence of additional copper ribbon resistance the above mentioned method was repeated for increasing interconnection resistances. In Fig.1 it can be seen that a ±3 % change in Jph can cause a difference of 0.9 % absolute in ηmod. In addition, the extra resistance due to interconnections leads to a steady decrease in output power and hence efficiency. Consequently, ignoring these two effects will cause erroneous estimation of module power.

3.2. Analysis of different cell sorting methods in low-light behavior

3.2.1. Usage of optical parameters in cell sorting methods

It is well known that STC are hardly applicable in most regions of the world. That is why it is of significant importance to analyze module power outcome at lower light intensities. To the best of our knowledge, sorting procedures until now are limited to electrical parameters only such as P_{MAX}, I_{SC} and I_{MPP}. Module efficiency, however, has a rather logarithmic dependence on irradiance [3]. Additionally, as the irradiance decreases J_{ph} decreases as well and mismatch effects in current will become more severe due to the increased influence of resistances.

In the second part of this study, to compensate these effects we analyzed different sorting approaches such as inclusion of weighted reflection R_w into sorting step. R_w is calculated for the used cells with the AM1.5G spectrum in the range 300 - 1200 nm. Its inverse proportionality with I_{SC} can be used to overcome the current mismatches at low irradiances. Fig. 2 shows the effects on η_{mod} and I_{SC} if cells are sorted by I_{MPP} and I_{MPP}/R_w.

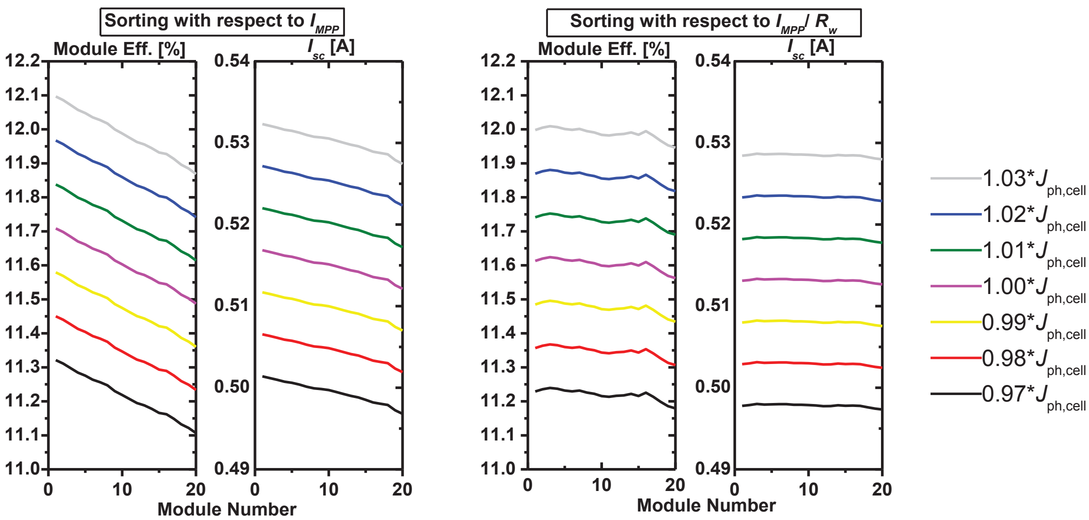

Fig. 2. Module efficiency and I_{SC} of simulated modules when sorted by I_{MPP} and I_{MPP}/R_w

In this simulation the interconnect resistance was set fixed at 1 Ωcm^2 and the irradiance level at 100 W/m^2. A combined sorting method with I_{MPP} and R_w does not necessarily provide a benefit if power is the concerned parameter of interest. However, since R_w^{-1} is an indirect indicator for I_{SC}, I_{MPP}/R_w can eliminate current mismatches. As shown on the rightmost graph in Fig. 2 this sorting method has the advantage to provide a stable current output for all the modules independent of their varying efficiency levels.

3.2.2. Analysis of R_{shunt} as a sorting parameter

The influence of R_{shunt} on the electrical characteristics of cells and modules at STC is minor. However, in reduced irradiation levels small R_{shunt} values have a direct influence on *I-V* curves. They cause increased slopes in the low voltage regime in the *I-V* curves and hence lead to pronounced current mismatches. This in turn affects the module performance severely in low irradiation. We analyze methods to overcome and suppress these effects with the integration of R_{shunt} in the cell sorting parameter set.

Reich et al. indicated a weak correlation between efficiency and R_{shunt} and concluded that sorting solely with respect to R_{shunt} may not be decisive [4]. In Fig. 3a one sample curve from Fig. 2 (sorting by I_{MPP}/R_w & $J_{ph,module} = J_{phcell}$) and the corresponding average R_{shunt} values are depicted. Although the values for R_{shunt} are relatively high to cause any significant deterioration on η_{mod}, the drop in efficiency for the modules in the rightmost part is closely coupled to the lower R_{shunt} values. As shown in [5] industrially tolerable but relatively small R_{shunt} values cause diminished module and cell performances at low-light. We analysed a combined sorting method including R_{shunt} at very low irradiances to overcome the mentioned effect and further to boost η_{mod} as shown in Fig. 3b.

Since for increased module performance high values of efficiency and R_{shunt} are required these two parameters were combined through their product. Cells were sorted in descending order and for module simulation the same approach described in section 3.1 was used. Fig 3b shows that at 50 W/m^2 irradiance a combined sorting by the product of R_{shunt} and efficiency performs better than that by efficiency only. By only applying this sorting approach an absolute efficiency gain up to 0.1% can be achieved. In this combined sorting method both parameters have equal weights and hence equal effect on η_{mod}.

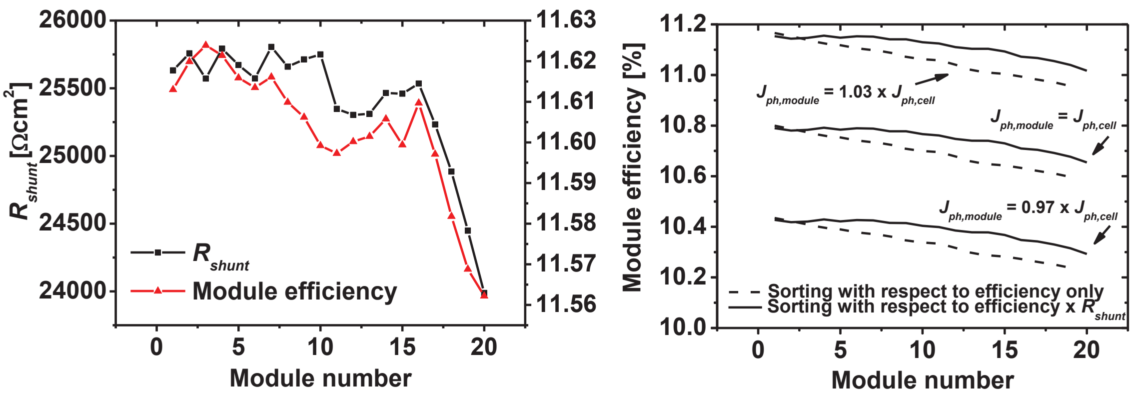

Fig. 3. (a) Effect of R_{shunt} on module efficiency at low irradiance (100 W/m^2) in case of sorting by I_{MPP} / R_w; (b) Comparison of sorting methods: Efficiency solely vs. efficiency x R_{shunt} at 50 W/m^2

It is important to note that at higher irradiances the influence of R_{shunt} on electrical characteristics is of minor importance. Fig. 4 shows the comparison of the two sorting methods at higher irradiations.

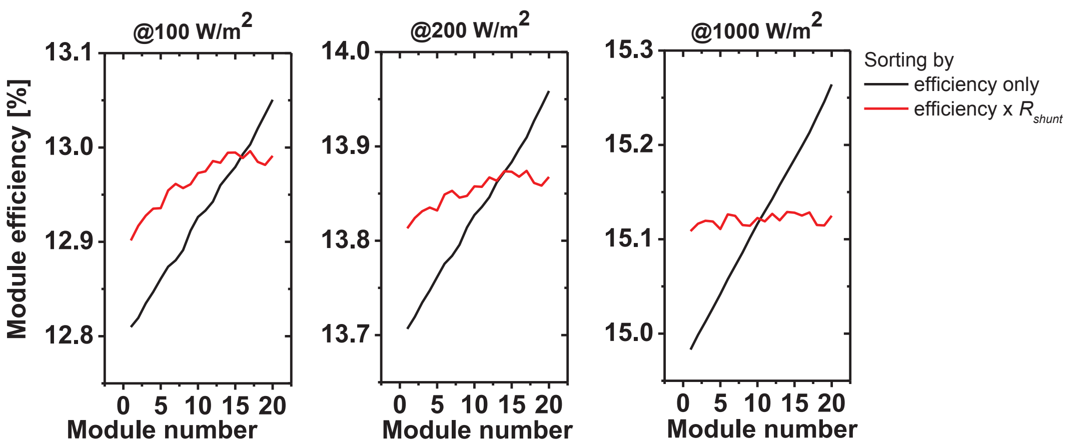

Fig. 4. Comparison of sorting methods (efficiency vs. efficiency x R_{shunt}) at different irradiations

Using the simple product (η x R_{shunt}) the dominant influence of η as a sorting parameter is suppressed by large R_{shunt} values. Another concern is that cells with high R_{shunt} values may have lower η compared to cells with greater η but smaller R_{shunt} values. Therefore this combined sorting presented here offers some advantage for areas with low level irradiation for long periods of time. If an overall performance increase is desired for all irradiation levels the weight of R_{shunt} should be gradually reduced for increasing irradiances. In an ideal case, combined sorting with R_{shunt} should increase η_{mod} at highest extent in low-light and should provide by STC very close η_{mod} to those obtained by sorting by η only. For this purpose the combined sorting method was changed to the form of (η + R_{shunt} / constant) to suppress the weight of R_{shunt}. Through optimization of the constant better and similar η_{mod} could be achieved for low-light and STC, respectively (Fig 5). With this sorting parameter set including η and R_{shunt} with the corresponding weights the overall η_{mod} can be increased.

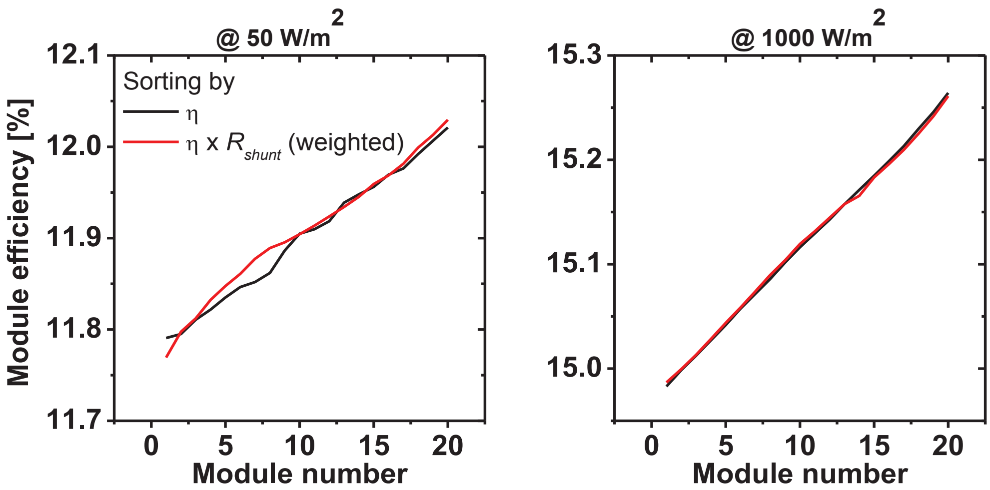

Fig.5 Comparison of sorting methods with respect to efficiency only and weighted combination of efficiency and R_{shunt}.

4. Conclusion

In this study we present new cell sorting methods considering different irradiation levels. For accurate analysis of module performance the role of encapsulation is taken into account. Considering R_w as an additional sorting parameter current mismatch in modules can be minimized at low-light. Moreover, inclusion of R_{shunt} into sorting allows achieving higher module efficiencies at low-light compared to conventional methods. Additionally, module performance can be increased for all irradiance levels using a combination of efficiency and R_{shunt} as sorting parameters through optimization of their weights.

Acknowledgements

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